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External Dose Estimation for Nuclear Worker Studies

E. S. Gilbert,[a,1] I. Thierry-Chef,[b] E. Cardis,[b] J. J. Fix[c] and M. Marshall[d]

[a] *Division of Cancer Epidemiology and Genetics, National Cancer Institute, Bethesda, Maryland;* [b] *International Agency for Research on Cancer, Lyon, France;* [c] *Pacific Northwest National Laboratory, Richland, Washington; and* [d] *Twin Trees, Besselslea Road, Blewbury, Oxon, United Kingdom*

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Epidemiological studies of nuclear workers are an important source of direct information on the health effects of exposure to radiation at low doses and low dose rates. These studies have the important advantage of doses that have been measured objectively through the use of personal dosimeters. However, to make valid comparisons of worker-based estimates with those obtained from data on A-bomb survivors or persons exposed for medical reasons, attention must be given to potential biases and uncertainties in dose estimates. This paper discusses sources of error in worker dose estimates and describes efforts that have been made to quantify these errors. Of particular importance is the extensive study of errors in dosimetry that was conducted as part of a large collaborative study of nuclear workers in 15 countries being coordinated by the International Agency for Research on Cancer. The study, which focused on workers whose dose was primarily from penetrating γ radiation in the range 100 keV to 3 MeV, included (1) obtaining information on dosimetry practices and radiation characteristics through the use of questionnaires; (2) two detailed studies of exposure conditions, one of nuclear power plants and the other of mixed activity facilities; and (3) a study of dosimeter response characteristics that included laboratory testing of 10 dosimeter designs commonly used historically. Based on these efforts, facility- and calendar year-specific adjustment factors have been developed, which will allow risks to be expressed as functions of organ doses with reasonable confidence.

INTRODUCTION

Epidemiological studies of nuclear workers are an important source of direct information on the effects of exposure at low dose and low dose rates and provide a valuable check on the validity of risk estimates obtained from studies of A-bomb survivors in Hiroshima and Nagasaki and of persons exposed for medical reasons. Workers involved in weapons production, nuclear power generation, and research activities have been studied, and results have been reported for workers at many different individual facilities. To increase statistical power and to summarize data from these studies, several combined analyses have been conducted including the ''IARC 3-country study'', an international effort coordinated by the International Agency for Research on Cancer (IARC) to combine data from nuclear workers studies in the United States, United Kingdom and Canada (*1*). In addition, IARC is serving as the coordinating agency for a collaborative study of about 600,000 nuclear workers in 15 countries (*2*). For additional background and discussion of nuclear workers studies, the reader is referred to Cardis *et al.* (*1*) and Gilbert (*3*).

A major advantage of nuclear worker studies is that doses have been measured objectively through the use of personal dosimeters, and dose estimates are generally available for each year of employment at the facility of interest. Many of the studies noted above have used these dose estimates to conduct dose–response analyses and have provided estimates and confidence intervals for the excess relative risk (ERR) per sievert. The resulting estimates are then compared with those from other sources, especially estimates that have formed the basis for radiation protection standards and that have been obtained from data on Japanese A-bomb survivors (*4*, *5*). For example, the IARC 3-country study estimated the ERR for leukemia to be about half the linear estimate obtained from male A-bomb survivors exposed between the ages of 20 and 60, but with 90% confidence limits ranging from about zero to about twice the A-bomb survivor linear estimate (*1*).

Clearly, the interest in comparing worker-based estimates with those obtained from high-dose data, and also the need to summarize data through combined analyses, means that attention must be given to potential biases and uncertainties in dose estimates. In particular, for the purpose of comparing worker-based estimates with those from A-bomb survivors, it is the absorbed dose to various organs that is of interest. However, the objective (*6*) of most current worker dosimetry systems is to estimate the Personal Dose Equivalent, known as *Hp*(10) (energy absorbed at a depth of 10 mm in tissue). In earlier years, the objective dose was not so clearly defined. The relationship of the recorded dose

[1] Address for correspondence: Radiation Epidemiology Branch, Division of Cancer, Epidemiology and Genetics, 6120 Executive Blvd., Room 7050, Rockville, MD 20852-7238; e-mail: gilberte@mail.nih.gov.

TABLE 1
Sources of Uncertainty in Estimates of Dose Obtained from Personal Dosimeters

Uncertainty source	Comment
Laboratory error	Sampling variation in measurements from film badges and thermoluminescent dosimeters
Energy response	Limitations in ability of dosimeter to respond accurately to all radiation energies in the work environment
Angular response	Limitations in ability of dosimeter to respond accurately to radiation coming from all directions
Calibration practices	Uncertainty in how dose calibrated and recorded, especially in early years
Conversion to organ doses of interest for epidemiology	Appropriate conversion depends on energy and geometry, which are not known with certainty
Practices used to measure and record very low doses	Particularly practice of setting doses below some ''threshold'' value to zero (a problem when dosimeters exchanged weekly)
Occupational dose received in the facilities other than those under study	
Dose from non-occupational sources	Natural background and medical exposures

value as an estimate of bone marrow dose or doses to other organs is complex, and it requires an understanding of the dosimetry system in use and the nature of the radiation environment (*7*). Many of the facilities under study began operations in the 1940s and 1950s and have experienced many changes both in dosimetry technology and in the kind of work that was performed. Obtaining the needed understanding to quantify biases in worker dose estimates is thus a challenging task.

SOURCES OF ERROR: OVERVIEW

Table 1 lists several sources of error in worker dose estimates. The most obvious source is the intrinsic sampling variation in measurements from film badges and thermoluminescent dosimeters. Such error, referred to as laboratory error, can be an important source of error in a single dosimeter measurement, especially for doses that are near the detection level of the dosimeter. As discussed toward the end of this paper, laboratory error is not likely to seriously distort dose–response analyses.

The errors that may be most important from the standpoint of epidemiology are those that result from the fact that dosimeters, especially those used in early periods of plant operation, were limited in their ability to respond accurately to all radiation energies to which workers were exposed or to radiation coming from all directions. Biases resulting from these limitations tend to be strongly dependent on the energy and geometry of the radiation exposure. Since, in many of the facilities that have been studied, workers were exposed under a wide variety of conditions (energies and geometries), and since the specific energy and geometry associated with any given recorded dose is usually not known, this can be a major source of uncertainty. In addition, the relationship of available recorded doses to the organ doses that are needed for epidemiology also depends on energy and geometry. Biases may also arise due to differences in calibration practices and the quantities measured in different countries and facilities. It is not always clear what was done in the early days, and this can increase uncertainty. Approaches for quantifying bias and uncertainty in estimates of external dose obtained from personal dosimeters are described in the next three sections.

Errors in worker doses can also result from practices used to measure and record very low doses. In some studies, including those of workers at the United Kingdom Atomic Energy Authority (*8*) and at the Oak Ridge National Laboratory (*9*), a special problem arose in the early period of operation when dosimeters were exchanged weekly, and doses below some ''threshold'' value were arbitrarily set to zero. Special methods have been used to address biases resulting from this practice (*8*). In addition, errors can result from not including the occupational dose received after workers terminate employment at the facility under study or from not including dose from natural background or from medical exposures. Such errors are difficult to quantify or to account for in dose–response analyses. Gilbert and Fix (*10*) conducted sensitivity analyses based on several assumptions regarding the magnitude of these biases for the Hanford data.

NATIONAL RESEARCH COUNCIL (NRC) COMMITTEE ON FILM BADGE DOSIMETRY IN ATMOSPHERIC TESTS

The first major effort to quantify bias and uncertainties in dose estimates obtained from film badge dosimeters was that of the National Research Council (NRC) Committee on Film Badge Dosimetry in Atmospheric Tests (*11*), who evaluated dose estimates based on film badge monitoring of persons exposed to radiation as a result of atmospheric testing of nuclear weapons between 1945 and 1962. This study is relevant because film badges (in addition to thermoluminescent dosimeters) were also used to monitor nuclear workers. This committee used independent lognormal distributions to express the bias and uncertainty from each of several sources (and for each of several atmospheric tests) and then combined these distributions to obtain an overall assessment. Unlike worker exposures, the radiation environment (energy and geometry) was fairly well characterized.

HANFORD WORKERS

Gilbert *et al.* (*12*) expanded the approach developed by the NRC to evaluate uncertainties in dose estimates for Hanford workers. In contrast to nuclear test participants, Hanford workers have been engaged in a variety of activities leading to exposure under a wide range of conditions (energies and geometries). Some Hanford workers also received a substantial portion of their dose from neutrons, and it is known that neutron dose was underestimated prior to the introduction of thermoluminescent dosimeters in 1972. Because of the difficulty in addressing uncertainties in neutron dose, these workers were identified for possible exclusion in dose–response analyses. These same workers were also those most likely to have been exposed to low-energy photons (<100 keV), which were also inadequately measured by early dosimeters.

The evaluation of dosimeter uncertainties thus focused on workers exposed to higher-energy photons in the range 100–1000 keV. For each combination of energy level (100–300 keV, 300–1000 keV) and geometry (anterior-posterior and rotational), and for each of four calendar year periods (1944–1956, 1957–1971, 1972–1983, 1984–1993), the potential bias from each of several sources was evaluated. The periods reflected changes in dosimeters or calibration practices. The evaluation of bias was based on historical data on dosimeter performance and on a laboratory study conducted specifically for this purpose. Biases were initially evaluated in terms of recorded doses as estimates of $Hp(10)$. Additional factors for converting $Hp(10)$ to estimates of doses to the bone marrow or lung were then obtained using published conversion factors (*13, 14*). The end result of this stage of the evaluation was a table of estimated factors for converting recorded doses to either bone marrow doses or lung doses, with entries for each combination of energy level, geometry and calendar year period.

These factors showed a strong dependence on energy and geometry. For example, in the period 1957–1971, the ratio of the recorded dose to the bone marrow doses was estimated to be 1.41 for a 100–300 keV source and anterior-posterior (AP) geometry, 1.79 for a 300–1000 keV source and AP geometry, 0.86 for 100–300 keV and rotational geometry, and 1.17 for 300–1000 keV and rotational geometry. Based on these estimates, weighted averages based on various combinations of energy and geometry could be obtained and are displayed in Table 2, which is taken from ref. (*12*).

Since the specific energy and geometry associated with any given recorded exposure are not known, it was necessary to obtain estimates of ''average'' exposure conditions. This was done by querying four health physicists with many years of experience in Hanford's dosimetry program, who each estimated the proportion of dose received with

TABLE 2
Combined Bias[a] for Estimating Red Bone Marrow Dose for the Multi-element Film Dosimeter Used at Hanford in the Years 1957–1971

Distribution by energy level, percentage from 300–1000 keV[c]	Distribution by geometry, percentage anterior–posterior[b]				
	0%	45%	60%	80%	100%
0%	0.86	1.07	1.16	1.28	1.41
40%	0.97	1.20	1.29	1.41	1.55
75%	1.08	1.32	1.41	1.54	1.69
95%	1.15	1.40	1.49	1.62	1.77
100%	1.17	1.42	1.51	1.64	1.79

[a] The bias is defined as the ratio of the recorded dose to the red bone marrow dose.

[b] The remainder of exposure is assumed to come from the rotational geometry.

[c] The remainder of exposure is assumed to come from the range 100–300 keV.

AP geometry (compared with rotational) and the proportion from energies in the range 300–1000 keV (compared with 100–300 keV). Based on their evaluation, the most likely values were estimated to be 75% 300–1000 keV and 60% AP. With this particular choice, the bias shown in Table 2 is 1.41. Based on the variation in the four responses of the health physicists, it was judged that the range 40%–95% would cover the proportion due to 300–1000 keV, and that 45%–80% would cover the proportion AP. From Table 2, it can be seen that these combinations lead to an uncertainty range of 1.2 to 1.6. That is, the recorded dose would be a factor of 1.2 to 1.6 higher than the bone marrow dose. However, additional uncertainties in the energy-geometry specific correction factors would increase this range.

IARC COLLABORATIVE STUDY OF NUCLEAR WORKERS

As mentioned at the beginning of this paper, a large collaborative study of nuclear workers in 15 countries is under way with IARC serving as the coordinating agency. This study was initiated in 1993 after an extensive feasibility study (*2*). Studies in many of the countries were initiated as a result of the IARC effort and involve new data, although the collaborative effort also includes studies in countries where findings have been published previously. The major objective of the study is to provide the large sample size needed to evaluate directly the risk of cancer (including specific types of cancer) resulting from low-dose chronic exposure to low-LET ionizing radiation. Estimates developed from this study will be compared with estimates that form the basis of radiation protection standards. Results from this study are expected soon.

An important component of this effort is an extensive study of errors in dosimetry, which was coordinated by a dosimetry subcommittee comprised of dosimetry experts from several of the participating countries (United Kingdom, United States, Canada, France, Australia and Japan), an IARC dosimetrist, and epidemiologists. The study is described in detail in a comprehensive report prepared by the dosimetry subcommittee (*15*). The objectives of the study were as follows: (1) to evaluate the comparability across facilities and time of currently available dose estimates; (2) to identify and quantify sources of biases and uncertainties in available dose estimates; (3) to recommend suitable quantities for the expression of dose data for epidemiological investigation; and (4) if possible, to propose conversion factors which allow approximate estimation of organ doses for specified exposure conditions. The study expands the efforts to address dosimetry errors in the earlier three-country study (*16*).

The study focused on workers whose dose was primarily from penetrating γ radiation in the range 100 keV to 3 MeV. Extensive efforts were made to identify the small fraction of workers who received substantial doses from neutrons, internal contamination, or photon radiation outside the range of 100 keV to 3 MeV. These workers will be excluded from most analyses because of difficulties in estimating their doses and because the objective of the study is to quantify the effects of chronic exposure to low-LET radiation.

The general approach to quantifying biases and uncertainties was similar to that applied to Hanford. This required evaluation of errors and uncertainties from each of several sources for each facility (with some countries having several facilities) and each period (reflecting changes in dosimetry systems, including calibration and recording practices, or in exposure conditions). The study included the following activities: (1) obtaining information on dosimetry practices and radiation characteristics through the use of questionnaires; (2) two detailed studies of exposure conditions, one of nuclear power plants and the other of mixed-activity facilities; and (3) a study of dosimeter response that included laboratory testing of 10 historical dosimeters. Each of these activities is described briefly below.

Questionnaires

Initial information on dosimetry practices was obtained from a questionnaire administered in 1990 during the feasibility stage of the study. A second detailed dosimetry questionnaire was sent out to participating countries and facilities in 1994 and included information on the following: (1) predominant energies and geometries of exposure; (2) dosimeters that were used (including types, characteristics of filters, and detection thresholds); (3) calibration practices and sources; (4) administrative practices such as criteria for monitoring, frequency of monitoring, and procedures used to handle below-threshold and missing doses; (5) neutron dosimetry; and (6) internal contamination. The dosimetry subcommittee reviewed results from this questionnaire at a meeting in 1996 and determined that more detailed information was needed for quantification of bias from various sources of error. A follow-up questionnaire was thus prepared and sent out in late 1996. For the 1996 questionnaire, it was specifically requested that the main study dosimetrist for the country see that each section of the questionnaire was completed by a person knowledgeable about the topic within each facility under study. The questionnaire included more specific questions on the main activities and sources of exposure in each of the facilities and asked experts to characterize the geometries of exposure in terms of percentages due to AP, isotropic and rotational exposure. Copies of the questionnaires and detailed summaries of the information obtained from them are found in Thierry-Chef *et al.* (*15*).

Studies of Exposure Conditions

Although the 1996 questionnaire provided additional information on exposure conditions, it was often difficult to be certain that different experts had interpreted questions in the same way. A particular problem was that it appeared that some experts classified geometry and energy levels in terms of the proportion of time spent in various exposure conditions rather than in terms of the conditions where the major part of the dose was received. To obtain a better characterization of exposure conditions, two special studies were undertaken, one of nuclear power plants and one of mixed-activity facilities. The dosimetry subcommittee had determined earlier that most facilities fell in one of these categories. Each of the studies included a detailed pilot study of a representative facility and a meeting of international dosimetry experts.

For the nuclear power plant study, the four plants in Switzerland were selected for the pilot study. The evaluation included careful study of the types of work during which workers were exposed, the main radiation sources, the average time spent in various areas where workers were exposed, and the impact of shielding and physical controls on the radiation fields. Based on this study, it was estimated that about 10% of the dose was due to photon radiation in the range of 100–300 keV and that about 70–80% of the dose was due to exposure with the AP geometry, with the percentage depending on the facility and on the time spent in routine maintenance. After this study, a group of international experts met to discuss both the questionnaire responses and the Swiss results. As a result of these discussions, it was concluded that on average, about 10% of the dose was from photon radiation in the range 100–300 keV (but could vary from 5%–20% for individual workers). Evaluating the predominant geometry was more difficult because it depends strongly on the type of work performed. It was eventually concluded that on average about 50% of the dose was due to exposure in the AP geometry and 50% in the isotropic geometry (but might range from 10 to 80% AP).

''Mixed activities'' facilities include those in which workers were involved in tasks related to all fuel cycle activities (fuel production, enrichment, reprocessing), waste treatment, research activities, radionuclide production, and military activities. Because these activities involve many different radiation sources and geometries, it is more difficult to develop estimates of ''average'' conditions than for nuclear power plants. A pilot study was carried out in the Saclay facility in France. For this study, the predominant exposure conditions were evaluated for nine installations on the site that were representative of the diverse activities. ''Average'' conditions were estimated by weighting the findings from the nine installations by the number of workers in each installation. In addition, a method based on information from dosimetric records was used to validate estimates of the proportion of dose in different energy ranges (*17*). To develop estimates of exposure conditions that might be applicable to all mixed facilities, a group of international experts reviewed the Saclay results, results of other relevant studies, and the questionnaire data. The other relevant studies included the study conducted at Hanford (described above), a study by the Personal Monitoring Services at the National Radiological Protection Board in the UK, and a study of Sellafield exposures (*18*). Based on this review, it was estimated that about 20% of dose was received on average from energies in the 100–300 keV range, with the remainder in the 300–3000 keV range. The range 15–25% was judged to describe the variation in this percentage both among installations and among workers. It was also estimated that about 50% of the dose was received in the AP geometry and 50% in the isotropic geometry. In this case, the percentage in the AP geometry was judged to vary from 40% to 55% among installations and to vary from 0% to 60% among workers.

Study of Dosimeter Response

To develop appropriate correction factors to account for dosimeter limitations, it is necessary to have information on how various dosimeters respond to exposure of various energies and geometries. To obtain this information, a review of the documentation on more than a hundred types of dosimeters that were used in the participating facilities was carried out. However, adequate information was not available for all dosimeters that had been used, especially older dosimeters. To obtain this information, laboratory experiments were carried out on 10 types of dosimeters, which were selected to represent the types of dosimeters most commonly used over the years of the study. The experiments were carried out at the IAEA Dosimetry Laboratory at Seibersdorf, Austria, and are reported in detail by Thierry-Chef *et al.* (*19*). Five dosimeters of each type were irradiated on a phantom for each combination of three photon energy levels (118 keV, 208 keV and 662 keV) and three simulated geometries (AP, rotational and isotropic). The simulated geometries were achieved by rotating the phantom in various ways.

The results of these experiments were then used to obtain the needed bias correction factors (and their uncertainties) associated with each energy/geometry combination. These results were then used to prepare tables somewhat analogous to Table 1 from the Hanford study for each dosimeter that was used. Information developed from the studies of exposure conditions could then be used to estimate overall correction factors for converting recorded dose to *Hp*(10), bone marrow dose, lung dose, or colon dose. Uncertainties in the estimated adjustment factors were also evaluated.

APPROACHES FOR ACCOUNTING FOR ERROR IN DOSE ESTIMATES IN DOSE–RESPONSE ANALYSES

Gilbert (*20*) discusses approaches for accounting for errors in dose estimates used in dose–response analyses of data from epidemiological studies of workers exposed to external radiation. These approaches are illustrated with analyses of data on workers at the Hanford site based on the evaluation of biases and uncertainties in these doses described above. In these analyses, recorded doses were first corrected for the systematic bias in these doses as estimates of organ dose with uncertainty in the correction factors reflected in the confidence intervals. These procedures did not greatly modify results for all cancer excluding leukemia, but the upper confidence limit for leukemia was increased by about 40%, a difference that is of some importance in comparing worker-based estimates and confidence intervals with estimates that serve as the basis of radiation protection standards. Error in the estimated correction factors was addressed as a systematic bias; that is, it was assumed that this error was perfectly correlated for all workers in the study. Because sampling uncertainty was large in this study, allowing for modest uncertainty in the adjustment factors (by conducting simulations) did not greatly modify results over those with no such allowance.

In addition to the uncertainty in the systematic bias, worker dose estimates are subject to laboratory error and to error from the variation in the energies and geometries among workers with any given recorded dose. Laboratory error, which is ''classical'' in form, might be expected to bias estimates of the ERR/Sv downward if not taken into account (*21*). However, Gilbert (*20*) and Gilbert and Fix (*22*) showed that such bias is likely to be trivial. This is because the larger cumulative doses, which are most influential in dose–response analyses, are almost always the sum of a large number of independent monthly (or sometimes weekly) dosimeter readings over time; thus the relative laboratory errors in larger doses are small.

Errors from variation in energies and geometries differ from laboratory errors in that they are unlikely to be independent for estimated doses at different times for the same worker. This is because there is undoubtedly a tendency for workers to remain in the same jobs in the same locations, where radiation environments remain reasonably constant. However, these errors would seem to follow the Berkson model and are not likely to seriously distort dose–

response analyses. Simulations might be conducted to address this source of error, but they would need to address the correlation structure, perhaps by making the overly simple assumption that errors at different times for the same worker were perfectly correlated.

Analyses that take account of dosimetry uncertainties are planned for the 15-country study. However, the simple approach taken for the Hanford data, in which it was assumed that the error in the correction factors was perfectly correlated among workers, is probably less appropriate in a study based on many different facilities and periods. Uncertainties in correction factors for different facilities are probably not perfectly correlated, but they are also unlikely to be independent since common assumptions were used in developing these factors. For example, results from testing a given dosimeter (in the study of dosimeter response) can be used for several facilities with similar dosimeters.

Although it may be difficult to fully account for dosimetry uncertainties in dose–response analyses, the extensive study of errors undertaken by IARC has nevertheless carefully documented various biases and uncertainties in a way that is comparable for all facilities and time periods. The use of the adjustment factors developed in this study will allow risks to be expressed as functions of organ doses with reasonable confidence and strengthens the basis for comparing worker-based estimates with those from other sources such as A-bomb survivors.

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